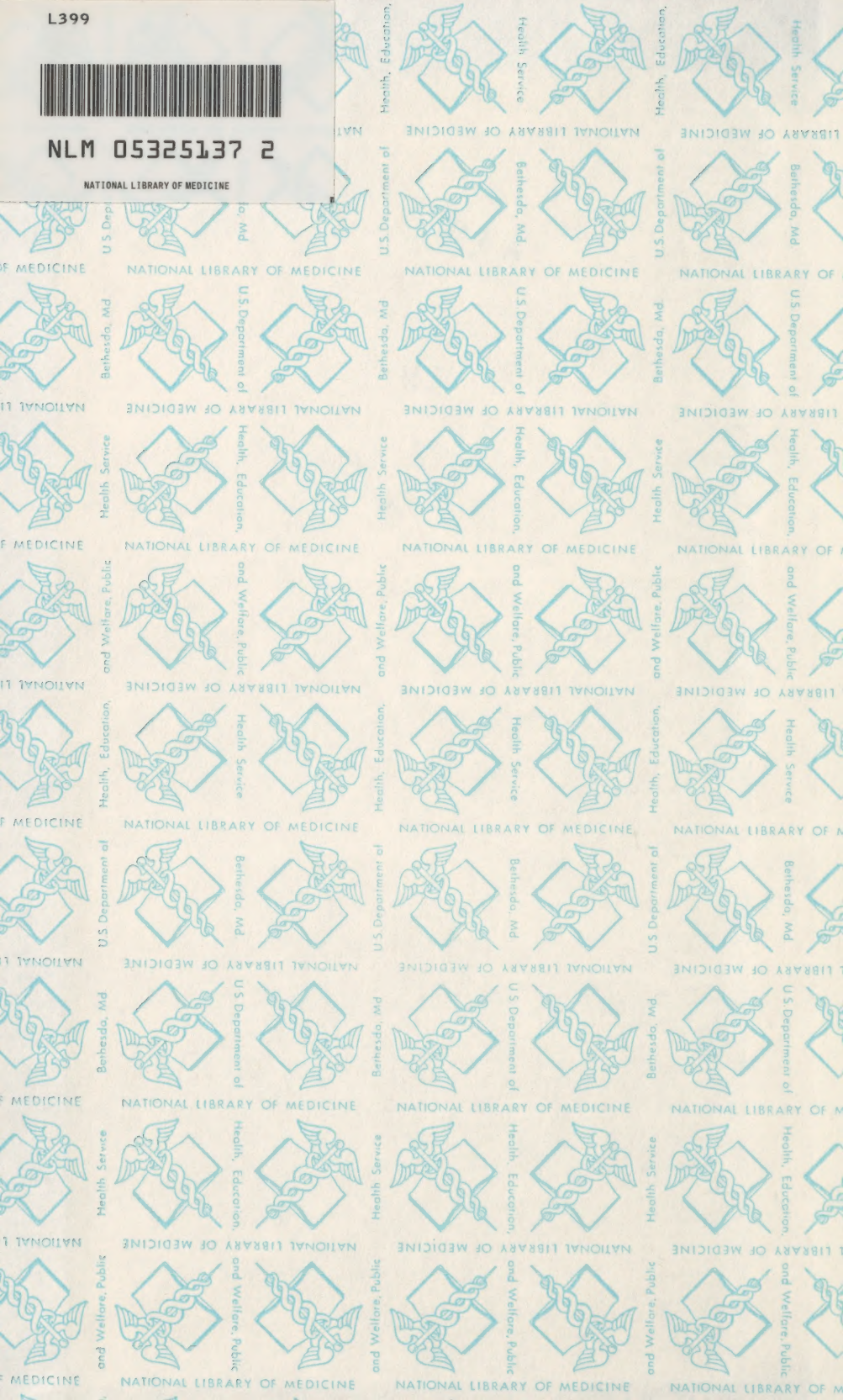






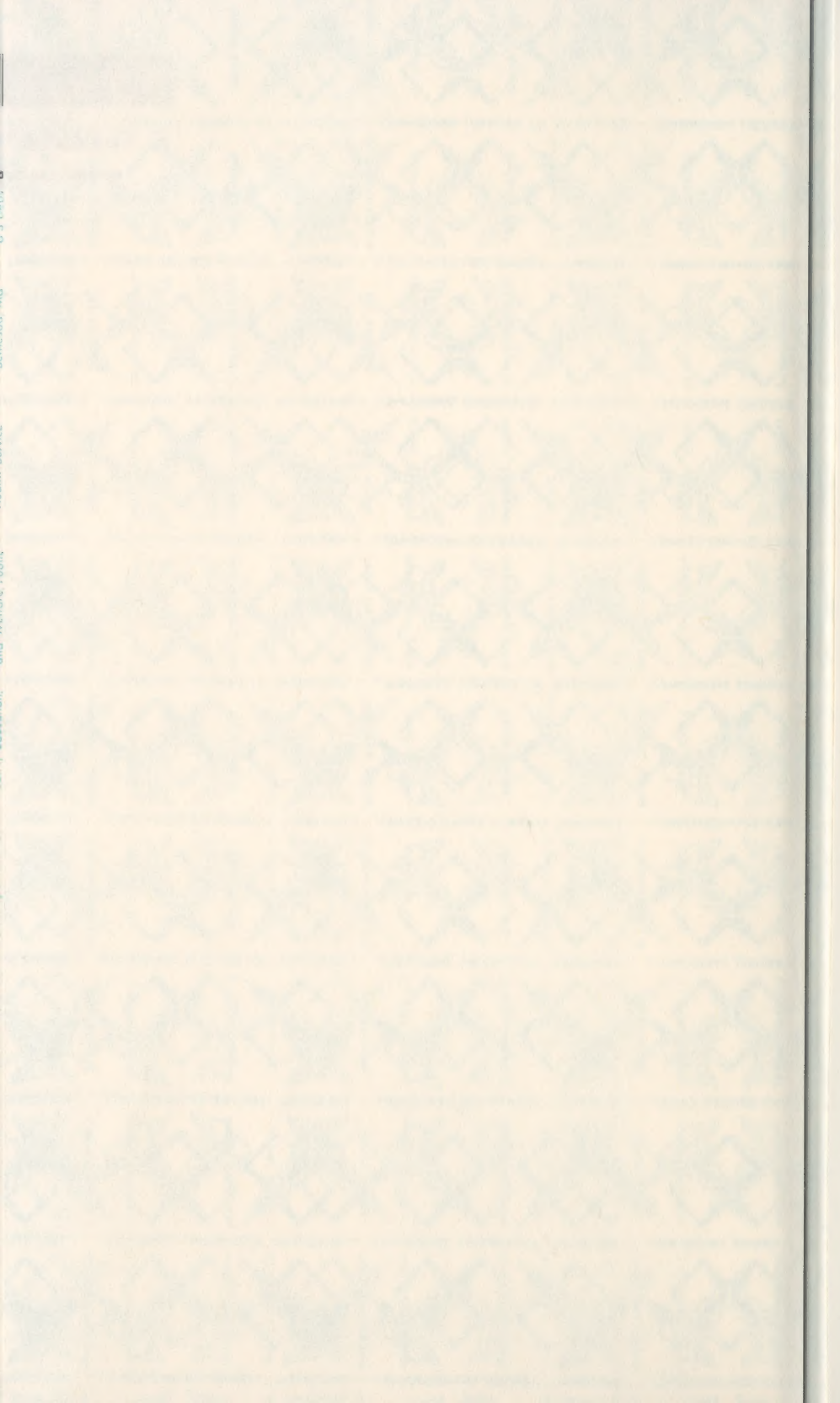
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# Carbon Monoxide Survey

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A Report on the Carbon Monoxide Hazard  
In Relation to Highway  
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CALIFORNIA HIGHWAY PATROL  
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Carbon Monoxide  
Survey

A Report on the Carbon Monoxide Problem  
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THE CARBON MONOXIDE HAZARD IN RELATION TO CALIFORNIA  
HIGHWAY TRAFFIC CASUALTIES

(Preliminary Report)

John P. Russell, M.D.\*, George S. Zelk\*\*  
and Fred R. Ingram, A. B.\*\*\*

INTRODUCTION: In 1937, out of a total of 37,968 traffic accidents on California highways, 597 were attributed officially to "sleepiness" of the drivers of vehicles involved. While fatigue due to long hours of driving and insufficient rest undoubtedly contributes to this condition, the theory has been advanced that carbon monoxide asphyxia due to the inhalation of engine exhaust gases is responsible wholly or in part for many of these otherwise inexplicable accidents.

In an effort to determine the relationship of carbon monoxide to highway traffic casualties, a survey of motor vehicles in operation on California highways has been conducted jointly by the California Highway Patrol, Department of Motor Vehicles; and the Industrial Hygiene Service, Department of Public Health. While the results of this survey are not complete, we believe that the information obtained so far is sufficiently consistent and significant to warrant this preliminary report.

PHYSICAL AND CHEMICAL PROPERTIES: Carbon monoxide is a colorless, almost odorless, tasteless, non-irritating gas, slightly lighter than air (specific gravity 0.967). It gives little or no warning of its presence when breathed into the lungs. It is produced by the incomplete combustion of fuels, such as wood, coal, gas, oil and gasoline, due to insufficiency of air or oxygen during the burning of the material. Although it is the cause of more deaths than all other gases combined, it is physiologically inert and non-poisonous in itself, except for its ability to deprive the tissues of oxygen. This effect is brought

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- Numbers in parenthesis indicate references to be found at the end of this article.

about by the combination of carbon monoxide with haemoglobin, the red coloring matter and oxygen-carrying element of the blood, rendering the haemoglobin incapable of carrying oxygen from the lungs to the tissues and organs of the body.

Haemoglobin has nearly three hundred times as great an affinity or attraction for carbon monoxide as it has for oxygen. Since normal air contains about 21% of oxygen, the presence in the air of only one three-hundredth of that amount of carbon monoxide, or about 0.07%, is sufficient, when breathed over an extended period, to saturate 50% of the blood haemoglobin and remove it from circulation as far as its oxygen-carrying power is concerned (1).

**PHYSIOLOGICAL EFFECTS OF CARBON MONOXIDE:** According to Sayers and Yant (7), the time necessary for a given amount of haemoglobin to combine with carbon monoxide decreases rapidly with increasing concentrations in the air breathed, until with 1.0% of carbon monoxide, a few breaths may produce a fatal blood saturation of 60% to 80%. The rate of absorption of carbon monoxide by the blood increases with physical exertion, due to increased rate and depth of respiration, and hence greater air intake. The same effect is produced by low oxygen content in the air breathed, as well as by high temperature and humidity. Long exposure to low concentrations of the gas causes more serious effects than short exposure to high concentrations with the same per cent of blood haemoglobin saturation, due to the longer time the body tissues are deprived of oxygen.

Persons with physical defects such as bronchitis, asthma, alcoholism, obesity, and chronic heart or vascular disease are particularly susceptible to the effects of carbon monoxide (8). There is no apparent variation in susceptibility due to sex (9).

When two individuals, one of whom is larger than the other, or when an adult and a child, both at rest, breathe air containing carbon monoxide, the smaller individual absorbs the gas more rapidly than the larger and tends to develop symptoms sooner, due to more active metabolism and greater volume of respiration in relation to volume of blood in the body (2).

Henderson and Paull (10) point out that in a man at rest, the tissues use little more than one-third of the oxygen carried to them by the blood, while during muscular exertion nearly two-thirds



is utilized. Therefore, the blood of a resting man may become nearly one-third saturated with carbon monoxide without causing appreciable symptoms; while if he puts forth any considerable muscular effort, the fraction of his haemoglobin remaining free from carbon monoxide is insufficient to transport the oxygen needed, and he may collapse. When his blood is more than half saturated, he may collapse even at rest. If he remains for any considerable time in this condition, the delicate nerve cells of the brain, and sometimes other organs as well, are injured by the continued lack of oxygen, and unconsciousness results.

**PATHOLOGY:** The pathological changes brought about by carbon monoxide inhalation are due to the oxygen starvation of tissues. If it is prolonged, there will be, in some cases, permanent damage to certain organs of the body, the central nervous system being most vulnerable (8). An extensive pneumonia is found in many fatal cases of carbon monoxide asphyxia; in others death occurs as a result of focal softening of the brain (1). In some cases no changes in the organs can be found after death. Kober and Hayhurst (4) mention degenerative changes, thrombosis, and hemorrhage in the brain, encephalitis, broncho-pneumonia, fatty degeneration in the blood vessels and other tissues, and extensive hemorrhage in the serous tissues, as being the most common pathological findings.

**SYMPTOMS:** The symptoms of carbon monoxide asphyxia may be divided into two stages (11). In the first stage, the victim may experience a sensation of tightness across the forehead, dilatation of cutaneous blood vessels, frontal and basal headache, throbbing in the temples, weariness, weakness, dizziness, nausea and vomiting, loss of strength and muscular control, increased pulse and respiration, and finally collapse and loss of consciousness. All of these effects are increased and accelerated by exercise because of the additional need of oxygen in the tissues. All of them are seldom experienced by the same individual. When the concentration of carbon monoxide in the air breathed is high, or when the victim is at rest, loss of consciousness may result without any of these warning symptoms. In the second stage, the blood pressure falls, muscular control is lost, reflexes are dulled and finally abolished, intermittent convulsions may occur,



breathing becomes slow and shallow, and finally ceases if exposure to the gas is continued.

Apparently some persons can become accustomed to long exposure to small amounts of the gas without serious injury, while others become permanently affected (12). Judgment is sometimes impaired to the extent that the victim of carbon monoxide fights with his rescuers when they attempt to remove him from the presence of the gas to fresh air (13). He may grow not only indifferent to the danger, but even soothed to drowsiness, a condition resembling alcoholic intoxication (8). He may develop hallucinations and wild mental pictures (4).

The effects of carbon monoxide on the human body are proportional to the factor obtained by multiplying the concentration of the gas in the air breathed by the period of exposure. When the concentration in parts per million, multiplied by the time in hours, gives a factor of 300, there is no perceptible effect. A factor of 600 causes a just appreciable effect; 900 causes headache and nausea; and 1500 is dangerous (2). Therefore a concentration of 100 parts per million may be inhaled for four or five hours, or a concentration of 400 to 500 parts per million for one hour, without appreciable effect. Concentrations of over 1500 parts per million, or 0.15%, of carbon monoxide are dangerous in one hour or less.

The relation of percent of blood saturation to physiological effect (2) is shown in the following table:

TABLE 1	
Percent of Saturation	Physiological effects
10	No appreciable effect except shortness of breath on vigorous muscular exertion.
20	No appreciable effect except shortness of breath on moderate exertion; occasionally slight headache.
30	Decided headache, irritability, fatigue, disturbed judgment.
40-50	Headache, confusion, collapse, and fainting on exertion.
60-70	Unconsciousness, respiratory failure, and death if exposure is long continued.
80	Rapidly fatal.
Over 80	Immediately fatal.

Figure 1, compiled from various sources (2,3,7,8,14,15,16)

illustrates graphically the relation between concentration of carbon monoxide in the air breathed, duration of exposure, blood saturation, and physiological effects.

**AFTER-EFFECTS:** The sequelae or after-effects of carbon monoxide inhalation may include headaches, muscular pains, long periods of unconsciousness, loss of strength, and mental derangements, such as loss of memory, paralysis, and temporary blindness (7). These effects are usually temporary, but may be more or less permanent, depending on duration of oxygen starvation, personal susceptibility, and physical condition before exposure. Pneumonia sometimes occurs during or after coma, particularly if smoke is breathed at the same time, or if the victim is not kept warm (13). Other after-effects noted include extreme nervousness, muscular twitching, tremors, insomnia, and emotional disturbances. Hamilton (8) states that the great majority of victims of carbon monoxide asphyxia recover without any lasting symptoms. Leschke (1) mentions disturbances of speech and hearing as possible after-effects.

**DIAGNOSIS:** The diagnosis of carbon monoxide asphyxia depends upon the history of exposure, the appearance of the victim, the symptoms of oxygen starvation, and, most important, upon the detection of carbon monoxide haemoglobin in the victim's blood. The latter is the only infallible diagnostic sign (7). A small amount of blood (0.1 cc) which can be obtained from a small puncture wound in the finger, can be quantitatively examined in a few minutes for carbon monoxide, and a true diagnosis made.

**TREATMENT:** Carbon monoxide is not burned to carbon dioxide or otherwise destroyed in the body, but is eliminated through the lungs when air free from the gas is inhaled (2). Therefore, the treatment of carbon monoxide asphyxia is based on the elimination of the gas from the body. The mechanism is the reverse of that of absorption. Fortunately, the combination of carbon monoxide with haemoglobin, while much more stable than that of oxygen and haemoglobin, is reversible, and carbon monoxide can be driven out of the blood by an excess of oxygen in the lungs, due to the pressure and mass action of the latter gas. As soon as the victim begins to breathe fresh air, the tension of carbon monoxide in the lungs is less than that in the blood,

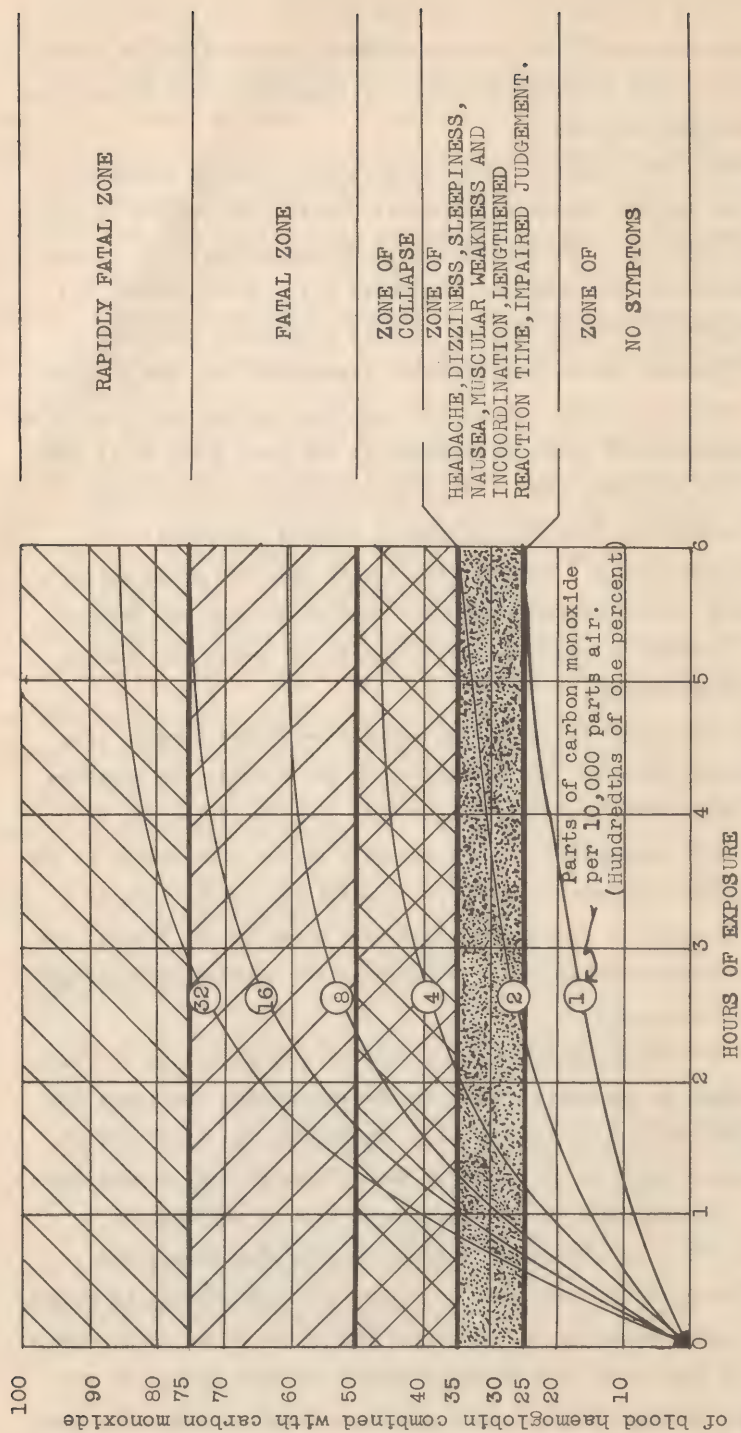


FIGURE 1 - EFFECT OF CARBON MONOXIDE INHALATION



and the gas passes from the blood to the air in the lungs, and is given off in the exhaled air. However, this normal elimination is slow, requiring many hours to wash out all of the gas in the blood. It can be greatly accelerated by increasing the amount of oxygen in the lungs, and by increasing the rate and depth of breathing. Both of these effects are produced by the inhalation of a mixture of 93% oxygen and 7% carbon dioxide, which removes the carbon monoxide from the blood five or six times as fast as normal air (7). If breathing has stopped, artificial respiration by the Schafer method should be given. Circulation should be aided by hot applications, physical exertion avoided, and any after-effects treated symptomatically. The best treatment of carbon monoxide asphyxia, of course, is prevention, and consists in avoiding as much as possible the breathing of air containing carbon monoxide.

**CARBON MONOXIDE CONTENT OF ENGINE EXHAUST GASES:** A running automobile engine produces about one cubic foot of carbon monoxide per minute for each 20 horse power (2), or enough to render the air in a single-car garage deadly within five minutes, if the engine is run with the garage doors closed. Henderson and his co-workers (3) state that carbon monoxide is the only considerable toxic constituent in the exhaust gas from gasoline engines.

Schumacher (4) gives the following average composition of gas collected from the exhaust pipes of gasoline motor vehicles:

Carbon monoxide	9.3%
Carbon dioxide	6.7%
Oxygen	1.4%
Nitrogen	82.2%
Illuminants	0.3%

According to Terry (5) there is no fundamental difference in the products of combustion of gasoline, butane, and diesel fuels which is inherent in the fuels themselves. The carbon monoxide content of the exhaust gas depends upon the air-fuel ratio furnished the engine, the type of engine, load, and speed. He states that gasoline motors usually operate upon a mixture which is from 20% to 30% too rich. Butane has better combustion characteristics than gasoline with respect to carbon monoxide formation: At the same air-fuel ratio the per cent of carbon monoxide is slightly lower with butane, and most butane-air mixtures are leaner than is customary with gasoline, giving a higher per cent of carbon dioxide and a

correspondingly lower per cent of carbon monoxide in the exhaust gas. Studies of European mine locomotives burning Diesel fuel (6) indicate that the carbon monoxide content in their exhaust gases is practically negligible, due to the great excess of air with which the motor operates. With a light load the excess of air is still greater. However, an appreciable amount of carbon monoxide is possible in Diesel exhaust fumes in case of motor trouble resulting in an excess of fuel oil being injected into the motor. German investigators have found that the carbon monoxide content of Diesel exhaust gas varies from 0.1% to 0.33%, depending upon the load and adjustment of the motor.

**ENGINE EXHAUST GASES IN RELATION TO PUBLIC HEALTH:** Recent studies indicate that there is not much danger of carbon monoxide asphyxia from inhaling exhaust gases in unconfined spaces, such as congested city streets (18). Tests made by Bloomfield and Isbell of the U. S. Public Health Service (19) in fourteen large cities showed an average concentration of 80 parts per million of carbon monoxide in the air of city streets at peak hours of traffic. The conclusion was reached that the traffic officer is the only individual possibly exposed to a potential health hazard from breathing street air containing automobile exhaust gas.

As a result of carbon monoxide studies made in Chicago's streets at various times of the day (20), it was concluded that the concentration of carbon monoxide in the air of city streets other than automobile boulevards is insufficient to constitute a serious public health hazard, but that at times the air of automobile boulevards contains enough carbon monoxide to menace the health of those exposed over a period of several hours, if their activities require deep and rapid breathing.

Graf and Gleeson (21) found carbon monoxide blood saturations ranging from 10% to 20% after one hour of driving a closed sedan with a blown-out exhaust gasket and a cracked exhaust manifold. They concluded that some danger to health exists if such exposure is continued for any considerable length of time, and that some of the road sickness encountered, as well as the feeling of fatigue frequently experienced by drivers and passengers of motor vehicles, may be accounted for by the presence of carbon monoxide.

In 1923, as a result of studies made in city streets,

garages, and repair shops, Henderson and Haggard (22) recommended the use of a vertical exhaust pipe on motor vehicles as a means of dissipating exhaust gases and thereby minimizing the health hazard involved in exposure to these gases.

Van Deventer (23) found that the drivers of five per cent of automobiles which he tested on the highway were exposed to over 300 parts per million of carbon monoxide.

In experiments upon eight normal men, Forbes, Dill, De Silva and Van Deventer (15) found that simple tests of reaction times, binocular vision and coordination of the hand and eye were unaffected by breathing carbon monoxide until the blood was 30% saturated. At 45% saturation, the performance was only slightly impaired. The subjects felt normal at 30% saturation or less, but at 45% they both appeared and felt unequal to driving a car because of inability to think of many things at once.

**INSTRUMENTS USED IN PRESENT SURVEY:** The concentration of carbon monoxide in the driver's compartment of the vehicles tested was determined by means of the portable M. S. A. Hopcalite carbon monoxide indicator. This instrument contains a small 6-volt electric motor which obtains its power from a storage battery, dry cells, or a transformer attached to a 110-volt light socket. Motorcycle batteries such as those used in highway patrol motorcycles were found to be the most satisfactory source of power for our tests because of their portability and capacity, and the fact that they could be recharged each night. The motor operates a vacuum pump which draws a sample of the air to be tested, at a fixed rate of flow (4.5 liters per minute) regulated by a manometer and valve, first through a dehydrating cannister filled with calcium chloride, then through a cell containing a battery of 48 thermocouples and a catalyst known as Hopcalite, which is a mixture of the oxides of manganese, copper, cobalt and silver. In the presence of this catalyst, the carbon monoxide present in the air passing through the cell combines with the oxygen in the air stream to form carbon dioxide. The amount of heat generated in this oxidizing process is directly proportional to the per cent of carbon monoxide in the air sample. The thermocouples in contact with the catalyst in the cell, generate electrical potentials in proportion to the temperature changes, and therefore in proportion to the amount of carbon monoxide passing through



the cell. These potentials are registered on an accurately calibrated millivoltmeter. Concentrations of carbon monoxide ranging from 5 to 1000 parts per million in the air sample tested can be read directly by means of this instrument. The indicating needle is set at zero by operating the instrument in fresh air before making a reading.

Since two of these instruments were available for making the tests, it was possible to check their accuracy at frequent intervals by comparing their readings, one against the other, in an improvised gas chamber (the highway patrol car used in the survey) filled with engine exhaust gas to a concentration of over 1000 parts per million carbon monoxide, which was allowed to seep out gradually through cracks around windows and floor boards.

Determinations of per cent of blood saturation with carbon monoxide were made by means of the pyrotannic acid apparatus devised by Sayers, Yant, and Jones (17). This method is based on the fact that a light gray-brown suspension is formed after a few minutes when normal blood diluted with water is treated with a mixture of equal parts of pyrogalllic and tannic acids, while in blood having carbon monoxide in combination with all of its haemoglobin, a light carmine suspension is formed. Gradations between these two extremes, representing percentages of blood saturation, give graduated shades between the gray-brown and carmine which can be read in comparison with a set of prepared standards representing varying but known percentages of blood saturation with carbon monoxide.

Determinations of wind velocity and direction were made several times daily with an Alnor velometer. Temperature and relative humidity readings were taken by means of a wet and dry bulb sling psychrometer. These readings were found to have little, if any, relation to the amount of carbon monoxide to which drivers of the vehicles tested were exposed.

**PROCEDURE IN MAKING TESTS:** Determinations of carbon monoxide in driver's compartments of motor vehicles were made in various parts of the state, as shown in Figure 2, on ascending and descending grades and level highways, under varying weather conditions, including snow, rain and desert heat, at various hours of the day and night, in temperatures ranging from 21° to 74° F., and relative humidities ranging from 18% to 97%.



At the start of the survey, a number of tests were made at one of the checking stations operated by the California Highway Patrol where out-of-state vehicles stop for registration. It was soon found, however, that determinations of carbon monoxide concentration made in the cab of a vehicle at a fixed point with the engine running and the vehicle at a standstill gave misleadingly high readings, due to accumulation of exhaust gases under the body of the vehicle and their leakage into the driver's cab. Comparative tests made on several vehicles showed that readings of from 600 to 800 parts per million of carbon monoxide obtained during standing tests dropped to 50 parts per million or less when the same vehicle was in motion. Since the purpose of these tests was to obtain a picture of actual operating conditions, the standing readings were discarded, and all subsequent tests were made during runs of at least five minutes duration on the highway.

The great majority of vehicles tested were trucks and busses, the only passenger cars included being those tested at the request of the owners. This does not mean that the cabs of trucks and busses are considered more apt to contain dangerous amounts of carbon monoxide than are passenger cars, but that the State Industrial Hygiene Service is particularly interested in the former class of vehicles, since the drivers of commercial motor vehicles are engaged in an industrial occupation in which exposure to carbon monoxide is a potential

occupational health hazard directly connected with their means of livelihood. Plans are being made by the California Highway Patrol to conduct similar tests on a large number of passenger cars in the near future.

Vehicles on which tests were made were taken at random as they came down the highway. The driver was signalled to stop, the purpose of the test was explained to him briefly, and his cooperation was requested. Splendid cooperation was obtained from both owners and drivers throughout the survey, and in no case was any objection made to having this test made. On the contrary, the owners of many vehicles tested requested that similar tests be made on other vehicles owned by them. After recording the time of test, weather conditions, type and age of vehicle, type of fuel burned, location and type of exhaust pipe, direction and grade of run, and load of vehicle, the tester entered the cab with the carbon monoxide indicator and battery and the driver continued on his way down the highway. Readings of carbon monoxide concentration in the cab were made continuously during a five minute run at normal speed. Whenever possible, comparative readings were made with windows both open and closed. In the great majority of cases, higher percentages of carbon monoxide were found with the cab windows tightly closed than when the windows were open.

The five minute test period not only gave an average carbon monoxide reading in the cab, but also gave the tester an opportunity to explain to the driver the purpose of the survey, the effects of carbon monoxide, the principle of operation of the recording instrument, and to obtain information concerning any symptoms referable to carbon monoxide inhalation, such as headache, sleepiness, weakness, and nausea, which the driver may have experienced. At the end of the test run, the driver was given a record of the results of the test, to be turned over to the owner, stating the amount of carbon monoxide found in the cab, with recommendations for correction of any defects noted in the exhaust system.

Table 2 gives the distribution of all vehicles tested by carbon monoxide readings obtained. Of the 1105 vehicles tested, 1083, or 98%, showed less than 100 parts per million of carbon monoxide in the driver's compartment. These results are shown graphically in Figure 3.



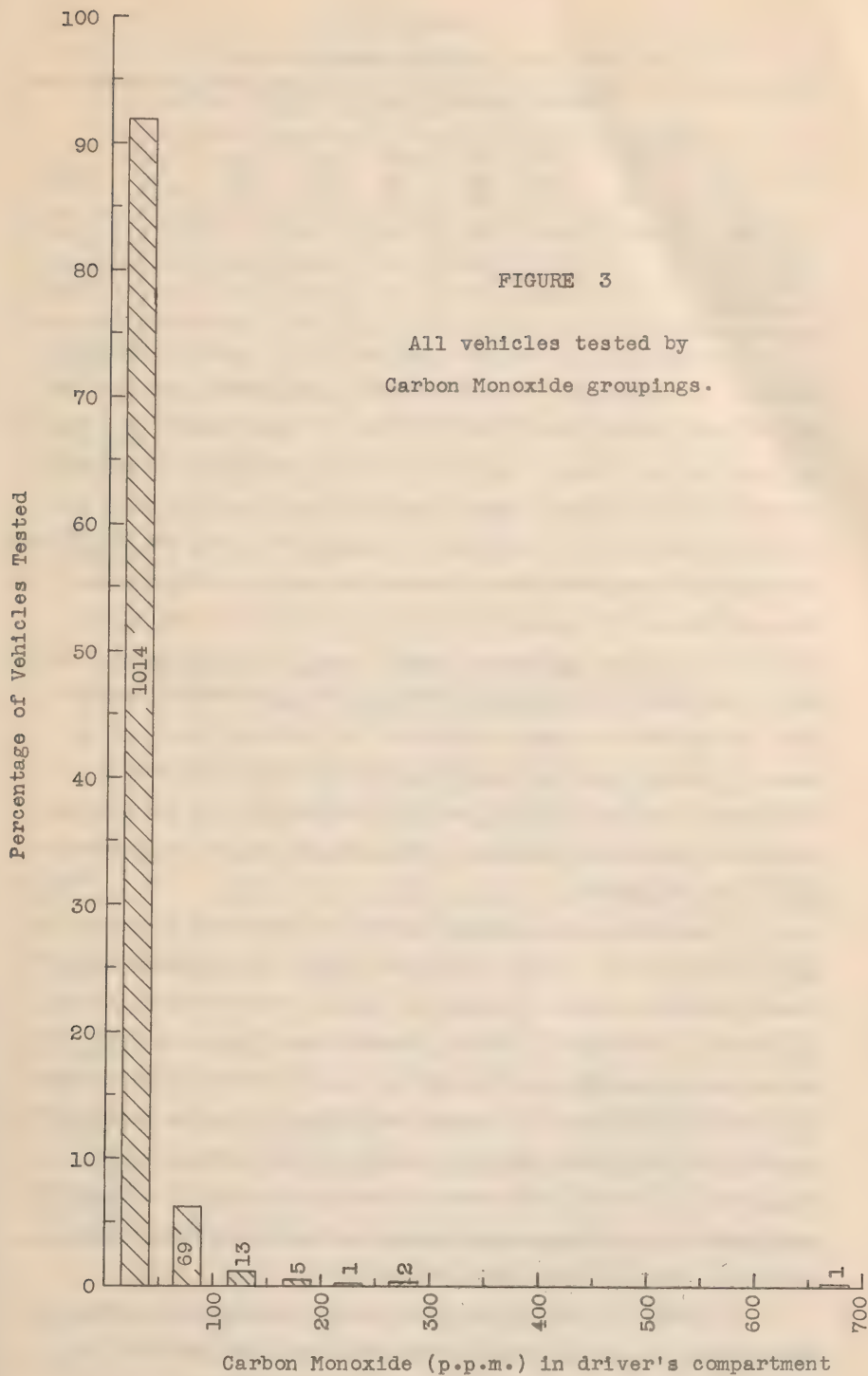


TABLE 2  
ALL VEHICLES TESTED

	Carbon monoxide concentration in parts per million							TOTAL
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	600 to 650	
No. of Vehicles	1014	69	13	5	1	2	1	1105
% of Vehicles	91.8	6.2	1.2	0.4	0.1	0.2	0.1	100%

Since 0.01% or 100 parts per million of carbon monoxide is sufficient in some cases to cause headache, sleepiness, and impaired judgment when inhaled over a period of six to eight hours, this amount was taken as the dividing line in classifying vehicles as being safe or potentially dangerous. When a reading higher than 100 parts per million was obtained in the driver's compartment during the five minute test run, an attempt was made to locate the source of the trouble. With the vehicle at a standstill, the hood lifted, and the engine running, the exhaust system was checked along its entire length, starting at the engine, by means of a flexible hose attached to the air inlet of the carbon monoxide indicator. In this way any point of escape of exhaust gas could be definitely located, since when the hose was held at the point of leakage, even when it was not apparent to the eye, the carbon monoxide in the escaping gas was registered at once by the instrument.

In Table 3 the vehicles tested are classified according to type of fuel burned. It was noted that none of the vehicles using Diesel fuel showed over 100 parts per million of carbon monoxide in the driver's compartment, although several were found with badly cracked exhaust manifolds. The exhaust gases escaping directly from these defects were found to contain percentages of carbon monoxide ranging from 100 to 500 parts per million, while readings taken in the stream of exhaust gases escaping from similar defects in vehicles using gasoline or butane showed concentrations of carbon monoxide greatly in excess of 1000 parts per million.

Table 4 lists the vehicles tested, classified according to type of vehicle. As previously mentioned, the great majority of vehicles included in the survey were trucks and busses.

TABLE 3

## ALL VEHICLES TESTED, CLASSIFIED BY FUEL USED

	Carbon monoxide concentration in parts per million							TOTAL
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	600 to 650	
GASOLINE Vehicles Per cent	877 91.8	62 6.5	11 1.1	3 0.3	1 0.1	1 0.1	1 0.1	956 100%
BUTANE Vehicles Per cent	77 87.5	6 6.8	2 2.3	2 2.3	- -	1 1.1	- -	88 100%
DIESEL Vehicles Per cent	60 98.5	1 1.5	- -	- -	- -	- -	- -	61 100%
TOTAL OF ALL VEHICLES	1014	69	13	5	1	2	1	1105

TABLE 4

## ALL VEHICLES TESTED, CLASSIFIED BY TYPE OF VEHICLE

	Carbon monoxide concentrations in parts per million							TOTAL
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	600 to 650	
Trucks Per cent	714 90.0	61 7.7	10 1.3	5 0.6	1 0.1	2 0.2	1 0.1	794 100%
Passenger Buses Per cent	105 98.2	2 1.8	- -	- -	- -	- -	- -	107 100%
School Buses Per cent	124 94.6	4 3.1	3 2.3	- -	- -	- -	- -	131 100%
Automobiles Per cent	71 97.4	2 2.6	- -	- -	- -	- -	- -	73 100%
TOTAL OF ALL VEHICLES	1014	69	13	5	1	2	1	1105

Table 5 lists the vehicles classed as potentially dangerous, in which the driver was found to be breathing over 100 parts per million of carbon monoxide during operation on the highway, indicating defects in the exhaust system which were located by the method



described above.

It will be noted that in each of these potentially dangerous vehicles, one or more of the following defects were found in the exhaust system:

TABLE 5 Vehicles with Concentrations of Carbon Monoxide of 100 p.p.m. or Over in Driver's Compartment

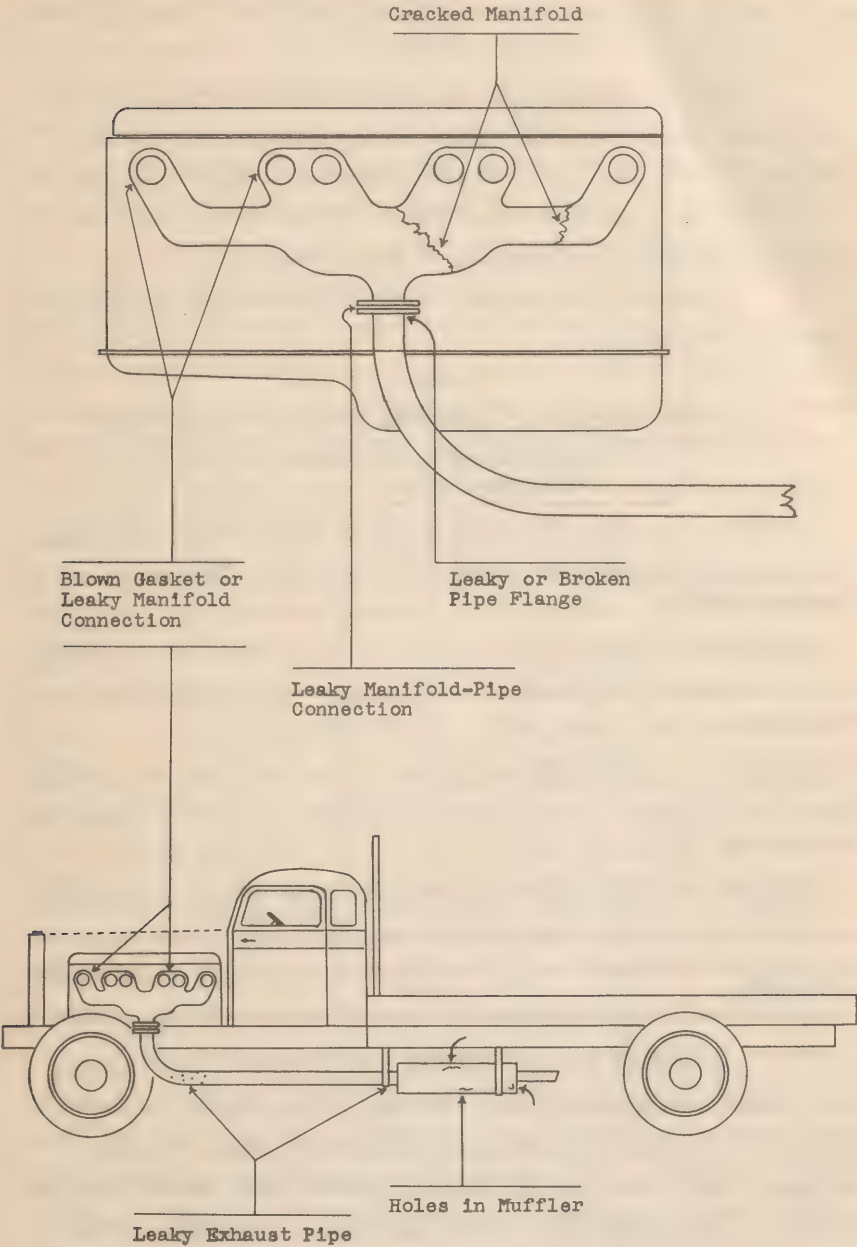
Type of Vehicle				Type of Fuel			Carbon Monoxide Reading (p.p.m.)	Defect Found in Exhaust System						Carbon Monoxide Reading (p.p.m.) After Emergency Correction of Defect
Truck	Truck and Trailer	Tractor and Semi-trailer	School Bus	Gasoline	Butene	Diesel		Blown Gasket	Cracked Manifold	Leaky Exhaust Pipe	Loose Manifold or Exhaust Pipe Connection	Leaky Muffler	Faulty Design	
x				x			150					x		
x				x			230	x				x		
		x		x			125				x			40
x				x			110	x	x					
		x		x			140					x		
		x		x			180	x						
		x		x			250	x						
		x			x		290		x					
		x		x			110	x						
		x		x			120	x						
	x			x			150	x						
	x			x			120	x						
x				x			100	x						
x				x			650		x		x			45
			x	x			110						x	
			x	x			135						x	
			x	x			100	x						
		x		x			140	x	x					
	x				x		150		x					
		x			x		105	x	x					
		x			x		175			x				
	x				x		120		x					

1. Blown-out exhaust gasket.
2. Cracked exhaust manifold.
3. Loose connection between exhaust manifold and engine or exhaust pipe.
4. Leaky exhaust pipe.
5. Hole in muffler.
6. Faulty design of exhaust system, resulting in exhaust gases being drawn into the vehicle by the fan of the cooling system.

Figure 4 indicates the location of those points in the exhaust system which were found to be the most common sites of leakage of exhaust gases.

In two of these vehicles, in which the emergency repair of the defect found could be effected on the spot, such as tightening of

Figure 4 - Schematic diagram showing defects and their locations, found in exhaust systems of motor vehicles tested.



a loose exhaust pipe connection, readings of carbon monoxide concentration made in the driver's compartment after correction of the defect showed that the amount of gas which the driver was breathing while driving the vehicle had been reduced well within safe limits by such repairs.

It was noted that in the absence of demonstrable defects in the exhaust system, slightly higher carbon monoxide readings were obtained in those vehicles with poorly fitting or no covering on the floor of the cab, and with large cracks and openings in the floor and dash which permitted the entrance of exhaust gases.

In Table 6 the vehicles tested are classified according to length of exhaust pipe.

TABLE 6  
ALL VEHICLES TESTED, CLASSIFIED BY TYPE OF EXHAUST PIPE

	Carbon Monoxide concentrations in parts per million							TOTAL
	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 650	
OVERHEAD PIPE								
Vehicles	88	-	-	-	-	-	-	88
Per cent	100	-	-	-	-	-	-	100%
LONG PIPE								
Vehicles	423	14	3	-	-	-	-	440
Per cent	96.1	3.2	0.7	-	-	-	-	100%
SHORT PIPE								
Vehicles	503	55	10	5	1	2	1	577
Per cent	87.2	9.5	1.7	0.9	0.2	0.2	0.2	100%
TOTAL OF ALL VEHICLES	1014	69	13	5	1	2	1	1105

The writers believe that the drivers of vehicles equipped with exhaust pipes ending under the body of the vehicle are more liable to be exposed to potentially dangerous amounts of carbon monoxide than in the case of vehicles equipped with exhaust pipes extending to the extreme rear end of the vehicle. However, in the present series of tests the number of vehicles included in each type of exhaust is insufficient to verify this belief. Further studies



are planned to determine, under controlled conditions, the relation between length and location of exhaust pipe and the amount of exhaust gases entering the driver's cab.

RELATION OF CARBON MONOXIDE TO DRIVING ABILITY: In an effort to correlate the effects of inhalation of engine exhaust gases with the ability to drive motor vehicles, five volunteers, including the writers, underwent a series of tests of their steering ability, perception and reaction time, eye-hand and eye-foot coordination, visual acuity, field of vision, depth perception, speed estimation, color vision, and glare resistance, before and after the inhalation of known amounts of carbon monoxide during a four-day period. These tests were made with the cooperation of the Division of Drivers' Licenses, State Department of Motor Vehicles, using instruments and apparatus assembled by them for measuring driving skill. The subjects were first given a series of tests on the instruments to reduce the learning or practice factor. Blood pressure and pulse readings were taken, and determinations of blood saturation with carbon monoxide by the pyrotannic acid method were made. The subjects then spent one hour in an improvised gas chamber, a closed sedan into which engine exhaust gas was introduced by means of a hose from the exhaust pipe. The concentration of carbon monoxide in the chamber, determined by the two carbon monoxide indicators used in the survey, was kept constant by admitting small amounts of exhaust gas from time to time to replace that which leaked out gradually. At the end of the period of exposure, blood samples were again tested, and driving tests were repeated. It was found that exposure to the gas had very little effect on blood pressure, pulse rate, steering ability, visual acuity, field of vision, color vision, depth perception, speed estimation or glare resistance. The results of these tests are given in Table 7.

The blood saturation readings are not considered reliable, due to inaccuracies in color standards which were not discovered until after the tests were made. However, they suggest that carbon monoxide when inhaled in small amounts day after day has a cumulative effect, and is not completely eliminated from the body in a few hours after exposure, as is commonly believed. Further tests along this line have been planned for the near future.

TABLE 7

## EFFECT OF CARBON MONOXIDE ON DRIVING ABILITY

Sub- ject Tested	1938 Date	Carbon mon- oxide Inha- lation		%Blood Hbg. Saturation With C.O.		Braking Time in Hun- dredths of One Sec. (average of 30 tests)			Subjective Symptoms After CO Inhalation
		Min.	P.P.M.	Before CO	After CO	Before CO	After CO	Differ- ence.	
JPR Age 37	3/31	60	600	5	25	58	61	+3	None
	4/1	60	600	15	45	61	66	+5	Slight Headache.
	4/2	60	900	30	55	58	62	+4	Slight Headache.
	4/4	60	600	25	45	60	59	-1	Slight Headache.
HH Age 35	3/31	60	600	5	25	66	67	+1	Slight Dizziness.
	4/1	60	600	25	40	67	71	+4	Slight Dizziness.
	4/2	60	900	30	55	65	69	+4	Dizziness, weakness in knees, tremor of hands, headache, mental con- fusion.
	4/4	60	600	25	45	65	68	+3	Dizziness.
GSZ Age 41	3/31	60	600	15	35	64	65	+1	Dizziness, headache,
	4/1	60	600	25	45	70	70	0	Severe headache, dizziness.
	4/2	60	900	30	55	71	74	+3	Dizziness, nausea, mental confusion.
	4/4	60	600	15	45	68	72	+4	Dizziness, headache, weakness in legs.
KS Age 25	3/31	60	600	10	25	64	64	0	Dizziness, muscular weakness, headache.
	4/1	60	600	20	40	62	66	+4	Sleepiness.
	4/2	60	900	25	55	61	63	+2	Headache, tremor of hands.
	4/4	60	600	25	40	60	63	+3	Headache.
FRI Age 37	3/31	60	600	15	30	57	63	+6	Dizziness, headache.
	4/1	60	600	25	40	59	58	-1	None
	4/2	60	900	30	55	54	56	+2	Tremor of hands, headache.
	4/4	60	600	25	50	58	61	+3	Headache, mental confusion.

CO Carbon monoxide gas.  
P.P.M. Parts of carbon monoxide gas to one million parts of air.

Braking time represents the interval, in hundredths of a second, elapsing between the appearance of a red light and the application of the brake by the subject, seated behind a set of standard automobile controls, following a moving road scene by manipulating the steering wheel. It was found that the inhalation of an amount of carbon monoxide considered equivalent to that breathed by the driver of a vehicle containing 100 parts per million of the gas during a six to nine hour driving period, caused a diminution in driving ability as indicated by headache, muscular weakness, tremors, mental confusion, and a small but definite lengthening of braking time. It is believed that this effect is greatly increased by fatigue such as is experienced by drivers of motor vehicles, particularly heavy trucks or similar vehicles. Plans are being made to conduct further tests under conditions more closely approximating actual driving conditions in order to minimize the learning factor and to include the fatigue factor in combination with exposure to carbon monoxide. Blood saturation determinations in connection with future tests will be made both by the pyrotannic acid method and by the gasometric method of Van Slyke and Neill (24) in order to insure accuracy of readings.

#### SUMMARY

1. Determinations were made of the carbon monoxide concentration in the air breathed by drivers of 1105 motor vehicles of various types during periods of actual operation of five minutes or longer on California highways under varying weather and road conditions.

2. In 2% of the vehicles tested, the carbon monoxide concentration was found to be 0.01% (100 parts per million) or higher. These vehicles are considered to be in a potentially dangerous condition, since this amount of gas may cause headache, sleepiness, weakness, impaired judgment, and decreased driving ability, if inhaled continuously over a period of time equal to a concentration factor of 900 according to the particular vehicle.

3. In each vehicle in which the concentration of carbon monoxide was found to be dangerously high (over 100 parts per million), the source of the trouble was traced to one or more of the following defects in the exhaust system: Loose exhaust pipe or manifold



connection, blown-out exhaust gasket, cracked exhaust manifold, leaky muffler, or faulty design of the exhaust system. Exhaust gases escaping from these defects may enter the driver's compartment in large quantities through openings in and around the cab without the driver being aware of their presence.

4. Correction of defects in the exhaust system greatly reduces the amount of carbon monoxide to which the driver is exposed.

5. Tests on human subjects indicate that the inhalation of 100 parts per million of carbon monoxide in engine exhaust gases over a period of six to nine hours renders the driver of a motor vehicle less efficient, and more liable to become involved in an accident on the highway.

#### CONCLUSIONS

1. It is believed that many otherwise unexplained highway accidents, in which experienced drivers, travelling along a straight highway in broad daylight after a good night's rest, run off the road or crash head-on into an approaching vehicle, are due to the driver's unknowingly breathing dangerous amounts of exhaust gases escaping from defects in the exhaust system of the vehicle he is operating.

2. In the absence of defects in the exhaust system, it is believed that there is little danger of carbon monoxide asphyxia from exhaust gases while driving along the highway.

3. The exhaust systems of motor vehicles should be inspected carefully and periodically for any defects which permit the escape of exhaust gases before reaching the exhaust pipe outlet.

4. Such defects should be corrected immediately to protect the driver from exposure to dangerous concentrations of carbon monoxide in the escaping gases.

5. Driver's compartments of motor vehicles should be fitted with tight floor mats to exclude exhaust gases which may enter through cracks around floor boards. Openings in the dash should be closed as tightly as possible.

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## PART II

### VARIANT FACTORS CONTRIBUTING TO CARBON MONOXIDE IN MOTOR VEHICLES

This section is to be considered separate from Part I, a preliminary report on "The Carbon Monoxide Hazard in Relation to California Highway Casualties" and should not be connected with Part I, except that some of the cases described herein were taken from data obtained in the survey upon which the report of Part I is based.

All data in Part I were taken from vehicles which had a reading of 100 P.P.M. (100 Parts of Carbon Monoxide to 1,000,000 Parts Air), which is considered by authorities on the subject to be a potential hazard. Part II of this report describes variant factors which contribute to the carbon monoxide hazard but which in themselves are not necessarily of sufficient concentrations to be considered a definite hazard.

Several vehicles tested did have definite leaks, but the reading was below the concentration of the arbitrary threshold of 100 P.P.M. As there were definite leaks from several different sources, it is considered that these factors should be given careful attention, in order to avoid any one of the factors from becoming a definite hazard. Also, in order to allow the owner of the vehicle to understand that which may cause trouble, and allow him to compensate for the faults before they do become dangerous, we will go over these different factors separately and endeavor to show why they should be given careful attention.

**SLEEVE CONNECTED MANIFOLDS:** It was noted that this type of manifold would sag in the center on some types, allowing the sleeve connection to separate or warp from the excessive heat, and allowing the exhaust gases to escape. On other types of sleeve fitting exhausts there was but one sleeve connection, owing to the fact that the connection depended solely on the machine fitting for support. The heat expands and warps this fitting, allowing the manifold to sag and separate. It is not desired to give the impression that the manifold completely separates or falls off, but it does permit a considerable leakage of the exhaust gases.

**FLEXIBLE TUBING:** The practice of using metal flexible tubing in various places in the exhaust system to take care of elbows and short



bends was noted quite frequently. From a safety point, flexible tubing should never be used in the exhaust system, although it is admitted it makes a very neat and easy way to construct the installation. Flexible tubing is not air tight, even when new, and it rapidly develops large leaks with use, due to vibration, wear, rust, and corrosion from the exhaust gases. It can readily be seen that this type of tubing embodied in any part of the exhaust system is undesirable, and is considered a potential hazard at any time it is used for this purpose.

A very careful study was made on this particular phase of the survey, and it was shown by test that every vehicle using flexible tubing in the exhaust system had a higher concentration of carbon monoxide gas in the driver's compartment than the same vehicle would have had if regular seamless tubing had been used.

A few vehicles were equipped with flexible tubing for the entire tail pipe, which is a very poor practice.

**BLOW-BY:** Blow-by is a constant source of supply of carbon monoxide gas into the driver's compartment, and in several cases this factor, alone, came within a few points of putting the vehicle in the dangerous zone.

Blow-by has several variant factors. In the first instance, in any motor that is badly worn, where the cylinders are out of round or the rings are worn, there is bound to be a large leakage of carbon monoxide gas past the rings into the crank case, and this leakage would naturally create a pressure in the crank case, causing a constant flow of carbon monoxide gas to come out of the breather pipe. It must, also, be understood that an engine in this condition would have much lower compression with reduced combustion efficiency; therefore, the carbon monoxide percentage of the exhaust gases would increase proportionately.

Another factor of blow-by is in a motor of the overhead valve type. This motor, when in good mechanical condition, is free from leaks, but with badly worn valve guides another outlet for exhaust gas is formed. In one vehicle a new set of valve guides was installed, and the leak was completely eliminated. Blow-by gases escape in the same manner through the valve guides of an "L" head

type motor except that the direction of flow will be through the crank case and out of the breather pipe.

The danger from blow-by is influenced by several factors such as headwind, tailwind, seal between motor and driver's compartment, and sealing of floor boards. Since the leak is in front of the driver's compartment, any aperture in the dash or floor boards would afford direct access to the driver's compartment.

**SHORT EXHAUST PIPES:** In starting the survey it was apparent that the length and direction of the exhaust pipes had a direct relation to carbon monoxide concentrations in the vehicle. It was decided that any exhaust pipe ending forward of the rear axle should be designated as a "short exhaust pipe"; if it ended to the rear of the axle, as a "long exhaust pipe"; and, one which projected vertically and ended above the cab, as an "overhead exhaust pipe."

It was found that the vehicles equipped with a short exhaust pipe had a consistently higher gas concentration reading than those with either the long pipes or overhead pipes, and the short pipe was proven to be definitely a contributing factor to the carbon monoxide hazard. For instance, reasonably low readings were taken in certain vehicles under motion, and the indicator immediately registered high readings when stationary, with the engine idling. The gas simply envelopes the vehicle. One test was recorded when the indicator registered a concentration of 850 P.P.M. with the vehicle standing, in a condition of slight tailwind, and only 45 P.P.M., moving up a steep grade with the same tailwind. One truck driver in this State met death, undoubtedly, from this condition, when, fatigued, he stopped his large truck at the curb and laid over the steering wheel for a few minutes to rest, letting the motor run. When the attention of passers-by was drawn to the apparently sleeping driver he was already dead. Other examples of this danger may be cited from data developed and information advanced in testing vehicles and discussions with responsible equipment superintendents.

Another phase of this problem in which the short pipe is a contributing factor was demonstrated in connection with a second contributing factor, which as pointed out above, either one might not in itself be dangerous but when linked with other factors are potential

hazards. One interesting example of this was found in a typical truck, the flat rack type with a header board mounted close to the cab. The test, with windows closed showed the carbon monoxide content to be 25 P.P.M. The windows were opened and the test continued. Unexpectedly the reading raised to 55 P.P.M. The usual investigation was made and it was found that the header board created a vacuum condition, pulling the exhaust gas along with the vehicle. The faster the vehicle moved the more the reading increased.

On that truck the exhaust pipe ended almost in the center of the vehicle and about 4 feet back of the header board, putting the exhaust gas directly in the vacuum field. The cab, of course, being immediately adjacent to the header board was enveloped by the resulting turbulence of the air and exhaust gas with the truck in motion and the gas readily entered the windows. With the truck loaded, the turbulent action, caused by the header board, is largely destroyed, the vacuum being created at the end of the load further to the rear, and the danger from that source is partially eliminated. Of minor importance, but still having a bearing on the problem is the effect on the gas, emptied under the truck by the short pipe, of deflection of the wind stream by obstacles such as the rear axle and tire carried under the body. Cracks in the body, or other openings, permit the gas to enter.

That the driver's cab is not the only important consideration in this respect was found in the test of some fifty trucks equipped with short exhaust pipes directing the exhaust into a rear wheel. This practice was held due to the common belief that the revolving wheel would create a turbulence, breaking up the concentration to a point of ineffectiveness. Tests, however, did not support that belief, especially with respect to the body back of the cab or in the rear of a bus. These parts consistently showed concentrations indicating an unsatisfactory condition for the carrying of men in those vehicles.

It should be mentioned that those vehicles included the utility truck commonly used for carrying men and equipment to the job and having a van type body or canvas covered top and sides with the rear entirely open.



An interesting and authentic account of one case came to light in connection with the test of one of these vehicles. During a public utility emergency a number of men were dispatched to the scene of trouble in the equipment truck. Upon arriving at the destination none of the men left the back of the truck. The driver investigated and found all men sleeping heavily. It developed that they had all suffered a case of asphyxia in minor degree from the carbon monoxide entering the rear of the body, due to the vacuum action described previously.

Tests made on this type of vehicle disclosed the carbon monoxide concentration related to the speed. At a speed of one to five miles per hour the concentration was 5 P.P.M., and at 35 miles per hour the reading raised to 85 P.P.M. A satisfactory correction of this dangerous condition was found in the installation of overhead exhaust pipes at the rear ending well above the roof.

MISCELLANEOUS FACTORS: During the survey eighty vehicles which were tested had definite exhaust defects but causing concentrations of an amount below the potentially dangerous point, (100 P.P.M.). Among such defects were the flexible exhaust coupling, leaking exhaust gasket, leaking manifold gasket, hole in muffler, defective exhaust pipe, blow-by, defective design, or poor sealing of engine cover in vehicle with cab over engine, loose or poor connection between manifold and exhaust pipe, and holes in exhaust pipe; the effect of wind is not to be overlooked, either.

As stated at the beginning of this article, one of these faults might not be of serious consequence at the time of test. However, on all vehicles that did have a concentration of 100 P.P.M. or above, the cause was definitely traced to one or more of the same defects. It is, therefore, logical to expect that the defects in all of those eighty vehicles would eventually develop leaks causing the same dangerous concentrations. Furthermore, while one of these single factors causes a concentration only of from 25 P.P.M. to 90 P.P.M., the combined resultant concentration of two minor defects might easily equal that of one serious defect. For example, a vehicle with a short exhaust pipe might gradually, through wearing of engine parts, develop blow-by and the combination of gas from these two sources could easily

amount to a dangerous quantity. In the interest of safety any defects of parts or design should be corrected and any danger eliminated. The nature of this problem is serious enough to warrant frequent inspection of the vehicle.

The influence of wind in these early tests is definitely regarded as another contributing factor, but inasmuch as our experiments with it thus far are limited, comment at this time will be limited to remarks in connection with photographs at the end of this report. This factor will have a place in future tests and experiments. Suffice it to say that without the aid of such factors as short exhaust pipes or burned out mufflers, it would not in itself be considered serious at this time.

**DESIGN DEFECTS:** In checking a number of the school buses it was found that there was considerable carbon monoxide in some buses, which was caused by faulty design.

This faulty design was found in every case to be either a vehicle of the pusher type or the cab over the engine. In such types the engines are mounted in the rear of the bus or inside the bus under a metal cover. In one instance where the engine and radiator were mounted in the rear of the bus, the exhaust pipe came out to the rear, placing the exhaust outlet directly under the bottom of the radiator. The fan, being directly behind the radiator, drew the exhaust gas back into the engine compartment. This compartment was separated from the passenger compartment by a wooden board partition, and a top cover which was loosely fitting provided access to the engine. It is very evident that there were two errors in this design; first, in the location of the exhaust pipe, and second, in having an engine compartment, in any event, which was not air tightly sealed to prevent the air from this compartment entering the passenger compartment.

This is in contrast with the same general design found in larger common carrier buses, not only with respect to sealing of the engine compartment, but sealing of the rear emergency exits and rear windows. The vacuum action created by the square rear end of a bus under motion pulls the gas into the bus through such cracks or openings. In the back of some school buses the indicator registered readings above that considered potentially dangerous, 100 P.P.M.

School buses must be especially well constructed and pro-

ected to prevent less concentrations than would ordinarily be considered dangerous, due to the effect of carbon monoxide on children. Research data points out that the same exposure more quickly and seriously affects children than it does adults.

The cab over engine, or engine mounted in the center of the bus, is generally covered by a steel hood with rubber seal around the bottom of the hood, this system being satisfactory as long as the seal is tight. However, any time this seal develops a defect, a potential hazard is created, and frequent inspection is necessary to guard against possible trouble.

At one location where tests were made, thirty school buses of the type with engine forward and outside of passenger compartment were tested. The exhaust pipes extended the entire length of the buses to the rear end, where an extension was welded, extending upward to a height of approximately one foot above the bus body. The tests proved this to be a very satisfactory type of installation.

**FLOOR BOARDS AND DASH:** Too much care cannot be given to these parts. A poorly sealed dash or floor is a danger at all times for the reason that if any leak develops in the engine compartment, such as a blown gasket, leaky exhaust connection or exhaust pipe, the driver would be subjected to the gas which would have very little opportunity for dilution with air. Also, they make an inlet for blow-by gases, as blow-by always comes directly from the engine compartment. Several vehicles were tested which had bad leaks under the hood, but had exceptionally good sealing, or tight floor boards and dash, with no holes or cracks, good rubber floor mats and rubber gaskets around steering column, clutch and brake pedals, and the transmission. Although these vehicles had the factors to make them dangerous, this tightly sealed driver's compartment had prevented the carbon monoxide from entering and accumulating to any extent. It will be noted that the words "driver's compartment" and "engine compartment" are used quite frequently, this being done to emphasize the fact that they are two different rooms. Engine room air is always potentially hazardous to breathe, regardless of its immediate condition.

**EXHAUST HEATERS:** There are types of exhaust heaters that enclose a part of the manifold, or a section of the exhaust pipe, for the heating element. An installation of this type which draws hot air from



around the manifold is considered dangerous for the reason that should the manifold crack, or a hole burn through the exhaust pipe in the vicinity of the heater, the exhaust would be drawn in and the occupants of the car asphyxiated. A very careful test was made on one vehicle equipped with a manifold type exhaust heater, after the occupants had all suffered seriously from asphyxia. The cause in this case was a hole burned through the exhaust pipe in the place where the exhaust heater was mounted around the exhaust pipe. The concentration was so high and the occupants were asphyxiated so quickly that there were no warning symptoms. In this particular heater, after a new exhaust pipe had been installed a test was made on the air at the mouth of the heater, and it still showed a reading of 75 P.P.M. This gas, it was indicated, was from other leaks around the engine, and while there were no blown gaskets, or cracked manifold, there were two or three very small leaks in sleeve connections, but they were sufficient to cause an undesirable concentration when drawn into the car by that type heater.

Corrections of defects were made on a number of vehicles, and after such correction the vehicles were re-tested. Such tests showed that the concentration of carbon monoxide had decreased to a negligible amount, thus demonstrating that prevention of the danger is largely a matter of occasional inspection and proper maintenance.

**FUELS:** Reference was made in Part I of this report to the carbon monoxide content of several motor fuels. In this connection, no mention was made, however, of one or two peculiar characteristics of these fuels which offer a serious possibility of leading drivers into trouble. The most outstanding example of this is in Butane. In testing a fleet of Butane trucks we were informed by the drivers that the tests were practically a waste of time, inasmuch as they had never smelled gas around the vehicles. They naturally were startled to see the indicator register high readings in several vehicles and did not either know or appreciate the fact that while Butane gas is practically odorless, it can produce a substantial amount of carbon monoxide. They thus had a false feeling of security, and, no doubt those vehicles had been neglected to some extent on this account.

The same will apply to vehicles using Diesel fuel. While the exhaust from this fuel ordinarily has very little carbon monoxide content, it is nevertheless capable of imperilling the driver's safety if the mixture is not proper and the exhaust pipe and other parts properly maintained.

In obtaining information relative to these variant factors contributing to the carbon monoxide hazard, exhaustive tests were made and very carefully analyzed; also, a number of experiments were performed to definitely establish as facts, or disprove as theories, certain conditions determined in connection with this study. It is hoped that this information will be of value to those persons or groups responsible for the safety of any drivers or occupants of vehicles on the highway, and to the automotive industry as well in the future design and construction of motor vehicles.

In an effort to graphically illustrate the path taken by which the carbon monoxide enters the cab, a truck of the conventional type was obtained and several photographs were taken under a series of controlled tests.

Picture No. 1 illustrates a poor type of floor board and dash. Note the large cracks around the entire floor board; also, large openings at left of steering column, transmission gear box, emergency brake, extra transmission, and battery inspection hole.

Picture No. 2 illustrates the flow of gas from a short exhaust pipe with a headwind. Note the turbulence of the gases and the trend in a forward direction following the bed toward the cab.

Picture No. 3 illustrates the same vehicle with a headwind, using a long type exhaust pipe. This installation affords better elimination.

Picture No. 4 illustrates this vehicle with an overhead type of exhaust. Note the dissipation of the gas above and free of the cab.

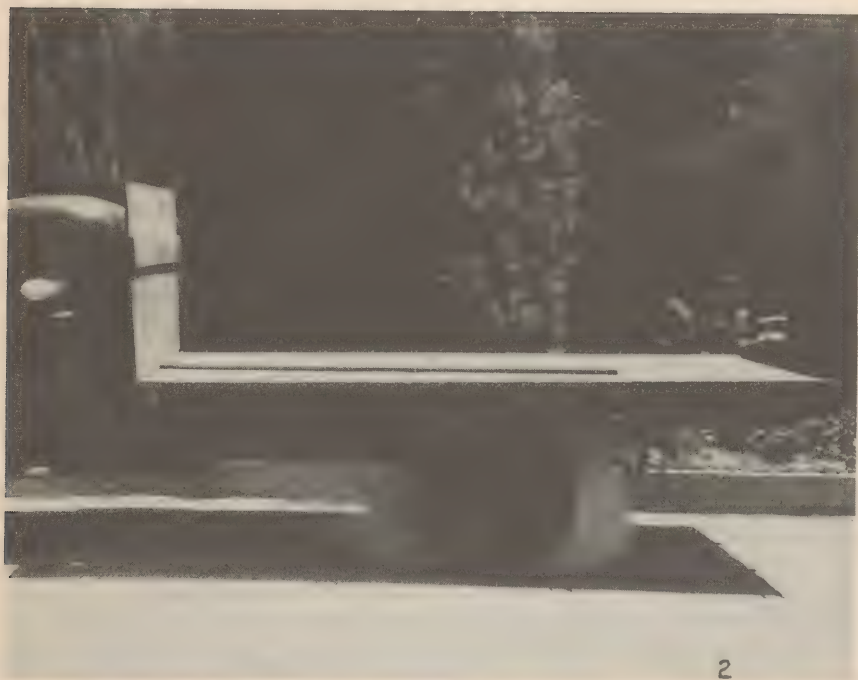
Picture No. 5 illustrates this vehicle using a short exhaust pipe with a tailwind. Note that the cab is practically enveloped by the gas.

Picture No. 6 illustrates the use of a long exhaust pipe. Note that the gases do not have the same tendency to follow the bed of the truck as with a short exhaust pipe.

Picture No. 7 illustrates the vehicle using an overhead type exhaust with a tailwind. It will be noted that the gases are completely above and free of the cab.

These pictures are actual photographs without any retouching. Smoke oil was used to make the exhaust gases visible, as the ordinary gases from a vehicle would not photograph, but this smoke would have no effect on the natural path of the exhaust gases.









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THE CARBON MONOXIDE HAZARD IN RELATION TO CALIFORNIA  
HIGHWAY ACCIDENTS

(SUPPLEMENTARY REPORT)

1 9 3 9

INTRODUCTION: In a survey conducted in 1938 by the California Highway Patrol, State Department of Motor Vehicles, in conjunction with the Industrial Hygiene Service, State Department of Public Health, 1105 commercial motor vehicles of various types were tested during five-minute runs on the highway, under varying weather and road conditions, to determine the amount of carbon monoxide in the air breathed by the driver. Two per cent of those vehicles were found to be in a potentially dangerous condition due to concentration in the driver's compartment of over 100 PPM (one hundred parts per million) of carbon monoxide gas. The presence of this amount of gas has been found to cause headache, sleepiness, weakness, faulty judgment, and impaired driving ability, if inhaled continuously for a time and of such concentration as to equal 900 (100 PPM x 9 hours, 300 PPM x 3 hours, etc.). In each vehicle in which the carbon monoxide concentration was found to exceed the toxic threshold, the source of the trouble was traced to some defect in the exhaust system, from which engine exhaust gas escaped and entered the driver's compartment, in most cases without the driver being aware of its presence.

The majority of vehicles included in the survey were trucks and buses, since the drivers of such vehicles are engaged in an industrial occupation in which exposure to carbon monoxide is a potential occupational health hazard directly associated with their employment.

In order to obtain a comparable series of tests on non-commercial motor vehicles (pleasure cars), and to study more fully the relationship of certain relevant factors, such as length of exhaust pipe, and driving with windows open and closed, a similar survey by the same group has been made of 1005 passenger automobiles.

The instruments used in this study were the same as those employed in the commercial vehicle survey. The carbon monoxide concen-

tration in the automobiles was determined by means of the portable M. S. A. Hopcalite Carbon Monoxide Indicator. Wind velocity and direction readings were made with an Alnor Velometer. Temperature and relative humidity determination were made with a Sling Psychrometer.

The two carbon monoxide indicators were calibrated daily, and the accuracy of their readings was insured by making simultaneous determinations with both instruments of the carbon monoxide concentration in our Highway Patrol car converted into a gas chamber by sealing cracks and then introducing engine exhaust gas with a hose.

PROCEDURE IN MAKING TESTS: The four mile section of U.S. Highway #70, between Blythe, California, and the Plant Quarantine Station at the State Line was selected as the location for the survey for several reasons. Since all automobiles entering California are required to stop at this station for inspection, this inconvenience to drivers and passengers, and interference with traffic, were minimized by starting the five-minute tests at this point. Also, most westbound automobiles make an uninterrupted run of 210 miles between Phoenix, Arizona, and Blythe, and most eastbound cars cover the 200 miles between Los Angeles and Blythe in one continuous travelling period; therefore, the majority of automobiles entering Blythe from either direction have been run continuously for several hours. It is under such conditions of prolonged exposure, that the driver and passengers are most likely to experience the toxic effects of relatively low concentrations of carbon monoxide in the car. Also, from this location several instances had been reported in which the occupants of an automobile reaching Blythe, after a continuous three or four hour run, had left the car, walked a short distance, and collapsed. Apparently, they had inhaled sufficient carbon monoxide from engine exhaust gases to build up a considerable carbon monoxide-haemoglobin blood saturation. As long as they were riding quietly in the car, their percentage of free haemoglobin was sufficient to meet the oxygen demand of their tissues, with no symptoms other than headache and slight nausea. When they left the car, the physical exertion of walking called for more oxygen than the partially saturated

blood could supply, and loss of consciousness ensued. The further investigation of these reports seemed necessary.

Official signs were posted at the Plant Quarantine Station, and four miles west of this point at the outskirts of Blythe to indicate the terminals of the five-minute test run. Automobiles to be tested were taken at random as they reached either of these terminals. After explaining the nature and purpose of the survey to the driver, the tester entered the car with the carbon monoxide indicator and rode to the other end of the test run, making a continuous reading of the carbon monoxide concentration at the driver's breathing level while the car was being driven at a normal speed. Comparative readings were taken with windows alternately open and closed. In case there was no room for the tester in the car, the front-seat passenger was asked to transfer to the Highway Patrol car, which followed the car being tested over the four-mile run. The most cordial cooperation was obtained from drivers and passengers of all cars included in the survey.

When the concentration of carbon monoxide in the car was found to be 0.050 percent, or higher, the source of the trouble was located by checking along the entire length of the exhaust system, from engine to tail pipe, with the car at a standstill and the engine idling. Large defects, such as broken mufflers and missing tail pipes, were obvious on visual inspection. Small but dangerous leaks in the exhaust system due to loose connections, defective gaskets, and very small holes, not always noticeable by visual inspection, immediately became apparent when the flexible hose attached to the carbon monoxide indicator was held at these points.

All defects found were pointed out to the driver with recommendations for correction.

It was noted that some vehicles had small holes drilled in the bottom of the muffler to let water escape. Since this practice is relatively new, special attention was given this item.

FINDINGS OF SURVEY: Of the 1005 automobiles in which determinations of carbon monoxide concentration were made, 975, or 97%, were found to

contain less than 0.01% of carbon monoxide in the air at the driver's breathing level, during five-minute test runs. Thirty cars, or 3% of the total number tested, contained concentrations of the gas in excess of this maximum safe limit. The distribution of all vehicles included in the survey, according to carbon monoxide readings obtained, is shown in Table 1.

TABLE 1  
ALL VEHICLES TESTED

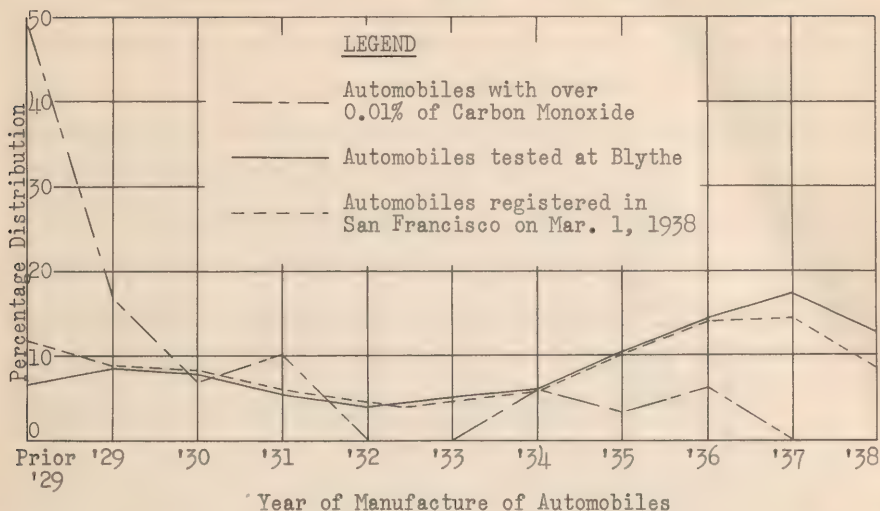
Carbon monoxide concentrations								
P.P.M.	0 to 49	50 to 99	100 to 149	150 to 199	200 to 249	250 to 299	300 to 349	TOTAL
Number of vehicles	933	42	18	4	4	1	3	1005
Per cent of all vehicles	92.8	4.2	1.8	0.4	0.4	0.1	0.3	100%

The percentage distribution, according to year of manufacture, of automobiles in which potentially dangerous amounts of carbon monoxide were found, is shown graphically in Figure 1. Fifty per cent of these cars were ten or more years old. The age distribution of all cars tested, and of 164,524 cars, representing the total registration in San Francisco on March 1, 1938, are shown on the same chart. Since complete statistics on the age of all cars registered in the State are not available, the San Francisco figures have been used as the next best basis for comparison. It will be seen that as a result of the random sampling procedure employed in selecting cars to be tested, the age distribution of the 1005 automobiles included in the survey closely parallels the San Francisco registration percentages, and may be considered fairly representative of conditions throughout the State.

The 30 automobiles found to be in a potentially dangerous condition due to the presence of more than 0.01% of carbon monoxide, the exhaust system defects responsible for this condition, and the carbon monoxide readings obtained with windows open and closed, are listed in Table 2.



FIGURE 1  
PERCENTAGE DISTRIBUTION OF AUTOMOBILES  
BY YEAR OF MANUFACTURE



The procedure was first to test the atmospheric contents of the car by tightly closing all windows, then the right front window was fully opened and the indicator permitted to register the reading. This window was again closed and the left front window fully opened for a time permitting a reading. A typical example shows the reading of 20 PPM with all windows closed, a reading of 70 PPM with the right front window opened, and a reading of 95 PPM with the left front window opened. To check against any errors in the machine or in readings the test was repeated completely.

Tests were, also, made with both front windows opened to determine the influence of the flow of air on the meter concentration readings. This test, likewise, showed definitely and repeatedly that the gas concentration actually increased due to the air current carrying gas into the interior of the car.

In the case just cited above the reading was increased to 110 PPM.

Reference to Table 2 discloses that the majority of high concentrations were obtained when both windows were opened.

Table 2

AUTOMOBILES WITH CONCENTRATION OF CARBON MONOXIDE OF 100 PARTS PER MILLION  
OR OVER AT DRIVER'S BREATHING LEVEL

Car Number	CARBON MONOXIDE PARTS PER MILLION				EXHAUST SYSTEM DEFECTS					
	All Windows Closed	R. F. Window Open	L. F. Window Open	Both Front Windows Open	Blow-by	Leaky Manifold- Engine Connection	Leaky Manifold- Pipe Gasket	Leaky Exhaust Pipe	Defective Muffler	Leaky Tail Pipe
1	115							X		
2	135								X	
3			115						X	
4	110								X	
5				160			X			X
6	115	125	325		X				X	X
7	20	70	95	110						X
8			65	225		X			X	X
9			125				X			X
10	50			150	X		X	X	X	X
11				300					X	
12			90	225					X	
13			135	60			X		X	
14	115		80	35	X		X		X	X
15			107	80					X	
16				110			X			
17	150	160	180	200				X	X	X
18			110	125						X
19				100						
20	15	103			X	X				
21	250	150	150	150	X	X		X		X
22	105	50	55	115	X			X		
23				300			X		X	X
24	85	200	200	200	X					X
25			50	110	X				X	X
26	110	105	110	50	X		X		X	X
27			110	115					X	X
28	25	15	20	110					X	X
29	50	95	95	150					X	X
30				150	X	X			X	X

Further study disclosed other factors related to the degree of the gas concentration. One was the relative direction of the wind in relation to the forward motion of the car, the gas almost invariably coming through the window on the lee side of the car. Another factor was the location of the exhaust system, which noticeably contributed to this condition if it too, was on the side of the vehicle opposite to the direction of the wind.

Pursuant to the search for the cause of higher readings with windows opened, it was found that when the leak was in the exhaust system to the rear of the dash and cowl, the concentration was increased upon opening the windows. When the leak was forward of the dash and cowl, the concentration decreased upon opening the windows.

In a majority of the cars, in which comparative readings could be made with all windows either opened or closed, the concentration of carbon monoxide at the driver's breathing level was higher with one or more windows opened than when all windows were tightly closed.

Great care was taken during the survey to prove or disprove these findings on open window gaseous conditions, and it is believed that sufficient evidence was gathered to show the fallacy of the widespread belief that open windows eliminate carbon monoxide gas from the vehicle, thereby protecting occupants from carbon monoxide asphyxia.

It was not possible to make comparative readings of all cars tested, as all were not completely equipped with window glass. In some instances the window glass would be broken in one car, or completely missing in another; therefore, the only reading possible to make under these conditions would be with a combination of windows open.

The explanation of higher gas readings with the windows open is apparently this: The motion of a car through the air causes high and low pressure areas in and about it. The pressure on the inside of a closed car is lower with respect to the pressure under the hood. Also it is lower than the pressure of the atmosphere around it, but low pressure areas likewise are created around projections on the car such as wind wings, window and door posts, etc. The lee side of the car is,

of course, a low pressure area compared to the side exposed to the wind. Since the low pressure areas are a tendency toward vacuum, the movement of air and gas is naturally from high pressure areas to lower pressure areas. When gas is present in the atmosphere about the car, opening the windows gives access to a lower pressure area and the gas, of course, moves into the car.

Similar explanation serves likewise in the second condition found, that of the gas concentration decreasing in the car when windows are opened, but the leak being forward of the cowl. The interior of the car is at low pressure compared to the area under the hood. The gas is drawn by the low pressure and driven by the action of the wind and fan. Opening one or more windows in this instance has a tendency to equalize the pressures inside and out; the entrance of the gas from the engine compartment through the floor boards, holes in cowl, and around pedals, is increased, but the concentration in the driver's compartment is reduced by the circulation and added volume of air.

In considering this new phase of carbon monoxide study gas concentrations in cars with open windows, one must not lose sight of the conditions previously reported and well known which relate to the high concentrations of gas which are possible, and which have proven fatal, in tightly closed cars. If there is a leak forward of the cowl, the pressure of air from the fan and movement of the car is certain to cause a motion of the gas through the cowl and floor boards if there are openings which will permit ingress of the gas. Opening the window under such circumstances would, seemingly, cause a circulation of air which might still result in carbon monoxide entering a vehicle, but, it is reasonable to assume, not to such a high degree due to the volume of air passing through it or at least circulating in the vehicle.

Instances were found where the apparent rule (that of gas concentrations being higher with windows open when the leak is to the rear of the cowl, and higher in a closed one when the leak is forward of the cowl) was not consistent; however, the deviation was so infrequent that it may be accepted as the rule. Likewise, there were several tests made



in which the opening or closing of the windows apparently had no bearing on the degree of the carbon monoxide concentration in the vehicle.

Suffice to say that the evidence obtained still supports our first conclusion that the only safeguard against carbon monoxide asphyxia is to maintain all parts of the vehicle exhaust system in good condition.

In each of the 30 automobiles in which a concentration of carbon monoxide in excess of 0.01% was found, the source of the trouble was traced to one or more of the following defects in the exhaust system:

1. Blow-by, or escape of exhaust gases from the breather pipe due to faulty seal between pistons and cylinder walls, or from worn valve guides.
2. Blown-out gasket or loose connection between exhaust manifold and engine or exhaust pipe.
3. Holes in exhaust pipe.
4. Holes in muffler.
5. Leaky connection between muffler and exhaust pipe.

The average carbon monoxide readings obtained in the 839 cars without defects, and containing less than 100 PPM of the gas, and considered not dangerous, are given in Table 3, according to wind direction and length of exhaust pipe.

TABLE 3

INFLUENCE OF WIND DIRECTION AND LENGTH OF EXHAUST PIPE ON CARBON MONOXIDE CONCENTRATION IN ABSENCE OF EXHAUST SYSTEM LEAKS								
TYPE OF EXHAUST PIPE	WIND DIRECTION							
	HEAD		TAIL		CROSS		TOTAL TESTED	
	No.Cars	Average CO Reading PPM	No.Cars	Average CO Reading PPM	No.Cars	Average CO Reading PPM	No.Cars	Average CO Reading PPM
Short Pipe	19	21	14	21	36	18	69	20
Medium Pipe	19	12	11	9	62	10	92	10
Long Pipe	160	11	86	6	432	10	678	9

Exhaust pipes designated as "short," include those ending under the body of the car, in front of the rear axle. Medium pipes are

those which carry the exhaust gas back of the rear axle but which end in front of a fender, bumper, or some other obstacle which may create a turbulence of the escaping gases. Long pipes are those which extend to the extreme rear end of the car, and provide for the unobstructed escape of exhaust gases.

In the absence of exhaust system leaks, the amount of gas reaching the breathing level of driver and passengers was found to be consistently greater in the case of cars equipped with short exhaust pipes, than in cars with long pipes, regardless of wind direction. These results were verified by making carbon monoxide readings in a highway patrol car equipped with a long exhaust pipe, during a ten-mile run which included head, tail, and cross winds, after which, first a short and then a medium exhaust pipe was substituted for the extended pipe, and carbon monoxide determinations were made in the same car over the same course, under identical wind and road conditions. The results of these comparative tests are given in Table 4.

Tests for carbon monoxide made in several new automobiles of different makes, during thirty-minute runs, over a fixed course, with head, tail, and cross winds, and with all possible combinations of front and rear windows open and closed, did not show the presence of appreciable quantities of carbon monoxide in the car. In every case, however, where holes were drilled in the muffler concentrations of gas were found in the vehicles. With no other faults, these concentrations varied from 10 to 65 parts per million; this quantity is not dangerous to adults but is actually a definite source from which carbon monoxide enters the vehicle. While the holes may extend the life of the muffler for a short period of time, this amount of gas eventually added to like amounts from other small defects may result in dangerous concentrations.

The results of these tests, made under controlled conditions, tend to substantiate the belief that drivers and passengers in cars which are free from exhaust system defects, are exposed to little, if any, danger of carbon monoxide asphyxiation on the highway, regardless of wind conditions and window adjustments.

TABLE 4

RELATION OF LENGTH OF EXHAUST PIPE TO CARBON MONOXIDE CONCENTRATION  
AT DRIVER'S BREATHING LEVEL

CARBON MONOXIDE READINGS - Parts Per Million														
Car Speed	Wind Velocity	Position of Windows During Test	Short Pipe			Medium Pipe			Long Pipe			AVERAGE CO READINGS		
			Wind direction with relation to car	Wind direction with relation to car	Wind direction with relation to car	Wind direction with relation to car	Wind direction with relation to car	Wind direction with relation to car	Wind direction with relation to car	Short Pipe	Medium Pipe	Long Pipe		
45 miles per hour for all tests	1,000 feet per minute for all tests	All windows closed	Right	Left	Head	Right	Left	Head	Right	Left	Head	29	10	1
			25	30	30	5	9	15	0	5	0	0		
			17	28	29	0	7	20	0	3	0	25	11	1
			8	25	25	0	12	23	0	5	0	21	13	2
			30	38	30	5	12	12	0	4	5	29	11	4
AVERAGE READINGS			20	30	29	25	2	10	18	16	0	4	1	3
GRAND AVERAGE			26			11			2					

This survey of a large number of vehicles clearly indicated that the age, make, or model, had little, if any, bearing upon the amount of carbon monoxide gas that would enter the driver's compartment.

If the mechanical condition of a vehicle is adequately maintained, there is little or no danger of asphyxia while driving on the highway.

To illustrate this, one vehicle, 1932 model, which had been driven for 207,000 miles, showed a concentration of only 17 parts per million. This small concentration was traced to "blow-by".

AN ACCIDENT AND SICKNESS: During the survey an accident occurred near Blythe, which furnished an opportunity for immediate investigation of the circumstances involved, and which is cited as an illustration of the accident hazard due to exhaust system leaks. On the afternoon of January 21, 1939, a 1937 sedan being driven at moderate speed, on a straight, level highway, practically free from traffic, left the road about ten miles west of Blythe, ran into the ditch, and turned over twice. One of the Highway Patrol officers of the survey party arrived at the scene of the accident a few minutes later. He noted from tire marks made by the car that the vehicle had wandered from side to side of the highway before leaving the road. A sample of the driver's blood, taken one hour after the accident, and tested by the pyrotannic acid method, showed that 18% of the blood haemoglobin was combined with carbon monoxide. Since it is generally accepted that about one-half of the carbon monoxide in the blood washes out in the first hour after removal from exposure to the gas, this test indicated that at the time of the accident the driver of the car probably had a carbon monoxide-haemoglobin saturation of about 35%. It has been demonstrated that this percentage of blood saturation with carbon monoxide is sufficient to produce headache, weakness, nausea, dizziness, sleepiness, faulty judgment, impaired driving ability, and in some cases unconsciousness. On questioning the driver of the wrecked car, it was learned that she had noticed a hissing sound in the engine shortly after leaving Indio,



about eighty miles west of the scene of the accident. She had paid no further attention to this noise, but had continued driving toward Blythe. She noticed a gradually increasing headache, and sleepiness, before losing consciousness. She had no recollection of events immediately prior to or following the accident. A careful inspection of the wrecked car made on the following morning, showed that it was in perfect mechanical condition except for a blown-out exhaust gasket between the manifold and exhaust pipe and several small holes in the dash between the engine compartment and body of the car. These defects were undoubtedly responsible for the escape of engine gases from the exhaust system, and their entrance into the car in sufficient quantities to cause partial asphyxiation of the driver. All the elements in the case, physiological effects, carbon monoxide-haemoglobin blood saturation, and exhaust system defects, fit together to complete a typical picture of an accident caused by carbon monoxide inhalation.

Sickness, as well as an accident, was found at the testing site. Several cars were stopped for test in which sick infants and young children were riding. While it was not possible to repeat tests after suggested correction of defects was made, and the findings are not conclusive, it is noteworthy that in every one of the cars in which sick children were found there was a substantial carbon monoxide concentration. In one case the car was defective to such extent and the infant so "car sick," the officers conducting the test required immediate correction of exhaust defects.

Although 100 PPM is the threshold of dangerous effect for adults, 50 PPM is recognized as the danger threshold for school children and, correspondingly, less for younger children.

#### SUMMARY

1. One thousand automobiles selected at random were tested during five-minute runs on the highway in the vicinity of Blythe, California, to determine the carbon monoxide concentration at the driver's breathing level.

2. In 3% of the cars tested, the carbon monoxide concentration

was found to be 0.01% (100 parts per million) or higher. These vehicles were considered to be in a potentially dangerous condition, since the inhalation of air containing over 0.01% of carbon monoxide continuously for a period of several hours may cause headache, sleepiness, weakness, impaired judgment, and decreased driving ability.

3. In each of the potentially dangerous vehicles, the source of the trouble was traced to exhaust gases escaping from one or more leaks in the exhaust system, such as blown-out gaskets, loose manifold and exhaust pipe connections, and holes in mufflers and exhaust pipes.

4. In a majority of the cars with exhaust system defects, the amount of gas entering the car was greater when one or more windows were open, than when all windows were tightly closed.

5. When no exhaust system leaks were present, the amount of carbon monoxide reaching the driver's breathing level was greater in cars having a short exhaust pipe ending under the body of the vehicle, than in cars equipped with a pipe which carried the gas to the extreme rear end of the vehicle.

6. Two-thirds of the automobiles containing potentially dangerous concentrations of carbon monoxide were found to have defective mufflers, from which engine exhaust gases were escaping in large quantities.

#### CONCLUSIONS

1. Carbon monoxide asphyxiation is responsible for many otherwise inexplicable highway accidents.

2. The underlying cause of this hazard is the escape of engine exhaust gases from leaks in the exhaust system and their entrance into the car in dangerous quantities.

3. The exhaust systems of motor vehicles should be checked carefully and frequently to detect the presence of any defects from which gases may escape before reaching the exhaust pipe outlet. The immediate correction of such defects is essential to the safety of the motoring public, as well as to the driver and passengers in the defective car.

4. Exhaust pipes should be extended to the extreme rear end of

the automobile, so as to provide for the unobstructed discharge and dissipation of engine exhaust gases into the atmosphere.

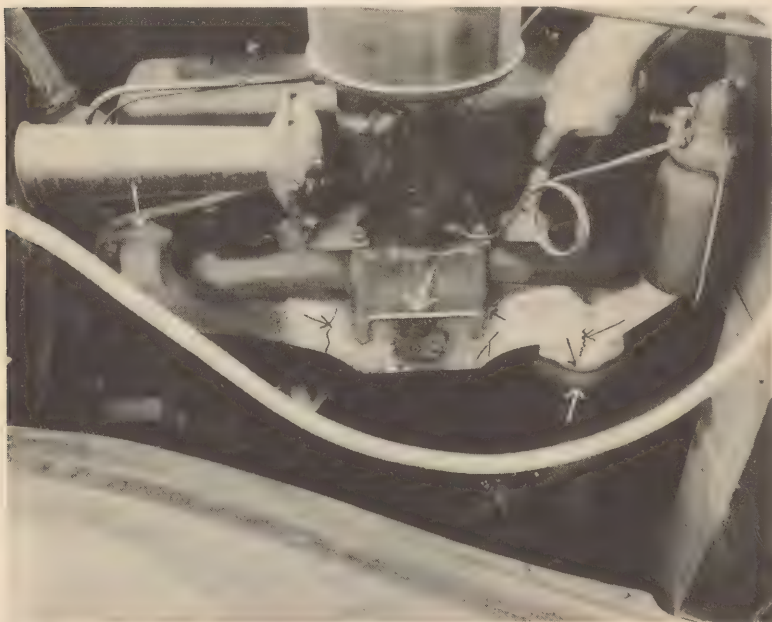
5. Mufflers should be constructed of heavy gauge metal, capable of withstanding ordinary wear and tear and the corrosive effect of exhaust gases. Rigid gas-tight connections should be provided between the muffler and exhaust pipes.

6. Keeping windows open while driving is not in itself insurance against carbon monoxide asphyxia.

7. There is little, if any, danger of carbon monoxide asphyxiation while driving along the highway, regardless of weather or road conditions or window adjustments, provided the exhaust system is free from leaks.



Illustrating means of calibrating the testing machines. The larger hose introduces exhaust gas into the car which is circulated by a fan. The smaller hoses are the usual sampling tubes, and extend into the center of the car, ending approximately one inch apart.



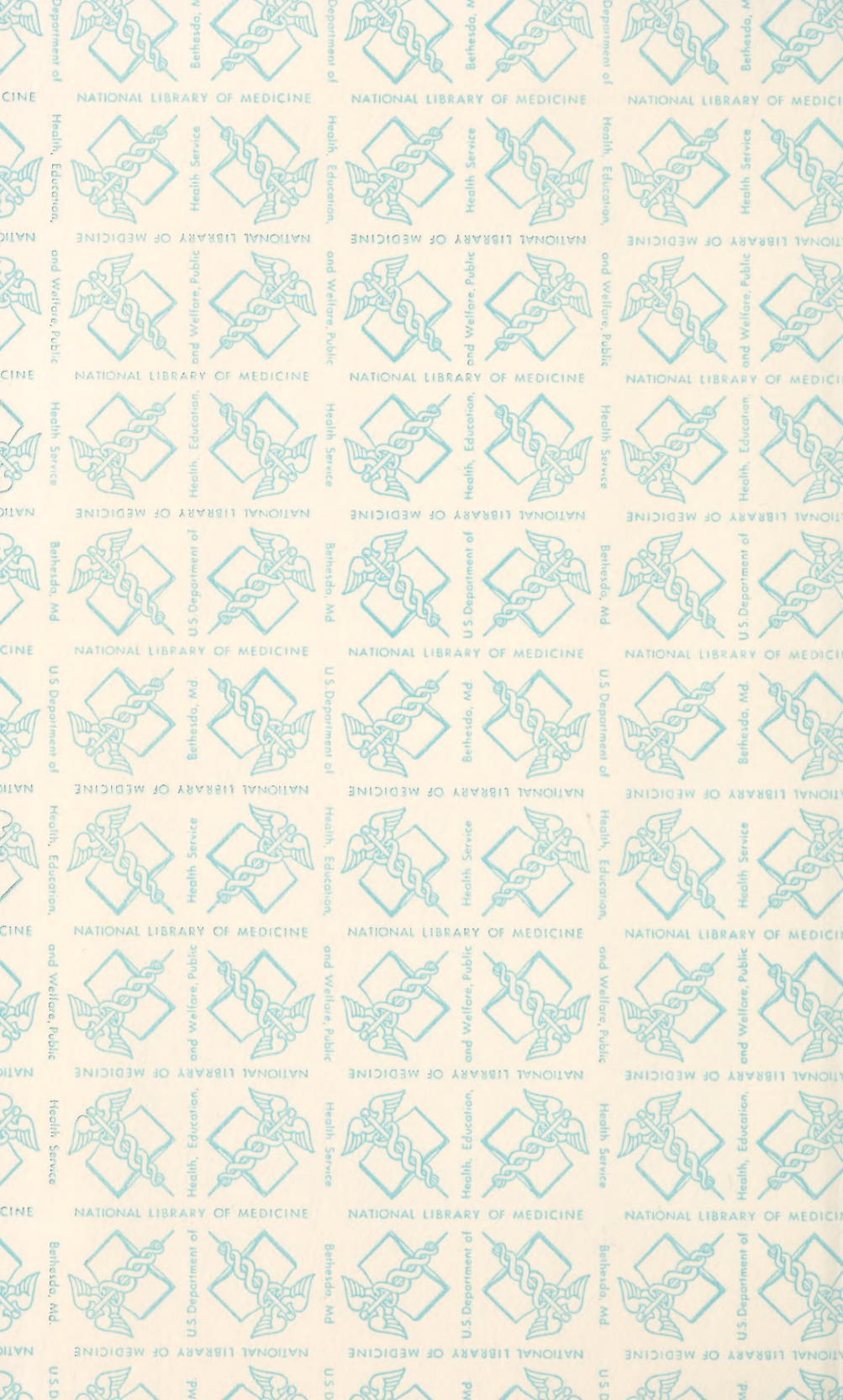
Showing the manifold of a motor and the points where leaks develop, as well as cracks, in manifold. Sample of air being taken at exhaust port.















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